Salish Sea Model - Continuing Development of New Capabilities and Applications

Scope of Work
for
Interagency Agreement between
US Environmental Protection Agency (EPA), Region 10 and
Pacific Northwest National Laboratory (PNNL)

January 30, 2018

Principal Investigator(s):
Tarang Khangaonkar, Program Manager – Coastal Ocean Modeling
Marine Sciences Laboratory / Coastal Sciences Division
Pacific Northwest National Laboratory
1100 Dexter Avenue, Suite 400
Seattle, WA 98109 USA
Tel: 206-528-3053
tarang.khangaonkar@pnnl.gov

Authoring Official:
Kevin L. Ghirardo, Sr. Contract Specialist
Business Systems Directorate
Pacific Northwest Division, Battelle Memorial Institute
Tel: (509) 371-7198
kevin.ghirardo@pnnl.gov

Project Manager/Officer: Tarang Khangaonkar, (206) 528, 3053, tarang.khangaonkar@pnnl.gov

Type of IA: "non-severable" Agreement. EPA: "Funds out". PNNL: "Funds in"

Authority: EPA Cooperating Authority: CWA 104(b)2

Requested Funding: $454,734 total for the two-year work plan. See attached Detailed Budget Sheet. **Year 1 Funding**: Tasks 1, 2, 3, and 6 - $267,799.

DUNS number: 032987476

Performance Period: October 1, 2017 to September 30, 2019

BUDGET	EPA TOTAL
Personnel	$146,721.00
Fringe Benefits	$42,573.00
Travel	$2,396.00
Equipment	$0.00
Supplies	$0.00
Contracts	$0.00
Other	$5,634.00
TOTAL DIRECT CHARGES	$197,333.00
Indirect Charges	$257,401.00
TOTAL	$454,734.00

Budget Proposal:

Task 1: Project Management, Meetings, and Development of a QAPP	$ 32,279.00
Task 2: Incorporation of TSS, Turbidity, and Light Availability in SSM	$ 93,638.00
Task 3: Addition and Testing of Eelgrass Module to SSM	$102,143.00
Task 4: Addition of Zooplankton Kinetics to SSM	$102,143.00
Task 5: Re-calibration of SSM with Zooplankton and Eel grass	$ 44,543.00
Task 6: SSM Plume Mixing and Transport Model	$ 39,739.00
Task 7: Report / Publication(s)	$ 40,248.00
Total:	$454,734.00

Background and Overview:

Pacific Northwest National Laboratory (PNNL) has developed a predictive ocean-modeling tool for coastal estuarine research, restoration planning, water-quality management, and assessment of response to future conditions (Khangaonkar et al. 2011, 2012, 2017)[1,2,3]. The Salish Sea Model (SSM) including the Puget Sound region in the state of Washington, and Georgia Basin in Canada, was developed using an unstructured grid framework specifically to function efficiently in conditions dominated by the complex shorelines and fjord like features. Numerous sub-basin-scale models from SSM have been already developed and used in shoreline modification and land-use feasibility assessments. Simulations of important nearshore processes such as circulation in complex multiple tidal

---

[1] Khangaonkar, T. and Z. Yang, 2011. A High Resolution Hydrodynamic Model of Puget Sound to Support Nearshore Restoration Feasibility Analysis and Design. *Ecological Restoration*. doi: 10.3368/er.29.1-2.173

[2] Khangaonkar, T. , B. Sackmann, W. Long, T. Mohamedali , and M. Roberts. 2012. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. *Ocean Dynamics*. (2012) 62:1353–1379.doi: 10.1007/s10236-012-0562-4

[3] Khangaonkar T., W. Long, and W. Xu. 2017. "Assessment of Circulation and Inter-Basin Transport in the Salish Sea including Johnstone Strait and Discovery Islands Pathways." *Ocean Modelling* 109:11-32.

channels, wetting and drying of tide flats, and water quality and sediment transport have also been successfully performed. The SSM is currently being used by U.S. Environmental Protection Agency (USEPA) and Washington State Department of Ecology (Ecology) for the analysis of circulation, water quality, and ecosystem response, for nutrient pollution management, sea level rise, climate change, and ocean acidification. PNNL modeling team has also conducted numerous applications of this tool to assist with nearshore habitat restoration planning and design, analysis in support of re-establishment of fish migration pathways, and assessment of basin-wide water quality impacts (see http://salish-sea.pnnl.gov/).

Researchers from various state and federal agencies, engaged in efforts related to restoration of Puget Sound continually encounter challenges that require hydrodynamic and water quality information. SSM has now reached a level of robustness that it can be used to address most of the basic information needs such as hydrodynamics (tides, salinity, temperature) and water quality (biogeochemical variables such as algal kinetics, dissolved oxygen, and pH) over annual biogeochemical cycles.

All models have limitations and uncertainties. These were previously identified and listed in the model calibration report (Khangaonkar et al. 2012).[4] Many of these limitations have already been addressed through on going work from 2013 to the present. Limitations of the model boundaries at Strait of Juan de Fuca and exchange through Johnstone Strait have been eliminated by expansion of the model grid around Vancouver Island and to the edge of the continental shelf. During that effort, new model capabilities including sediment diagensis and carbonate chemistry were also added. The model is therefore able to simulate sediment oxygen demand and sediment carbon and nutrient fluxes and address ocean acidification. Other ongoing improvements include transition from using uniform meteorological forcing to spatially distributed meteorology and the development of high-resolution embedded models of selected sub-basins. These sub-basin scale models are being developed and tested through funding from a joint USEPA / US Army Corps of Engineers grant and include improvements to accommodate intertidal functions and wetting and drying routines. The performance and skill of the biogeochemical component is expected to improve in the future with the expectation that data on phytoplankton community structure and primary production data, including carbon concentrations will become available through Puget Sound Marine Monitoring programs.

The SSM in its present state is therefore ready for application to specific questions related to water quality and ecosystem management and support implementation strategies for Puget Sound restoration. However, there is always room for improvement as new questions and queries for model use come up. We have an opportunity for addition of selected capabilities that will allow USEPA, Ecology, PNNL, and other state agencies to respond to the needs of Salish Sea Restoration community even better and with a broader reach. Improving the model performance in priority areas with a focus on exposure and vulnerability of shellfish to toxics, storm water runoff, submerged aquatic vegetation,

[4] Khangaonkar T, W Long, B Sackmann, T Mohamedali, and M Roberts. 2012. *Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate Scale Water Quality Model*. PNNL-20384 Rev 1, prepared for the Washington State Department of Ecology (Publication No. 12-03-049), by Pacific Northwest National Laboratory, Richland, Washington.

ocean acidification, and restoration of salmon habitat will continue to be our long-term goal.

Based on this understanding, PNNL is pleased to submit this Scope of Work to continue the development and application of the Salish Sea Model. Through this *Intergovernmental Agreement* (IGA) between PNNL and USEPA, we expect to provide continuous support to USEPA and partner agencies for the development, maintenance, and future applications of SSM.

Project Summary:

The proposed scope of work is based on numerous discussions with USEPA[5] and includes tasks designed to take the existing SSM biogeochemical model to a complete nutrient-phytoplankton-zooplankton-detritus (NPZD) style formulation. The detritus in FVCOM-ICM (the biogeochemical or water quality code in SSM) is addressed through dissolved and particulate organic carbon components. This effort will include addition of eelgrass through the submerged aquatic vegetation module and will result in improvements to nutrient interactions between phytoplankton, eelgrass, and sediment fluxes simulated in SSM. The effort will also include addition of TSS for computing turbidity plumes to accurately represent light availability and explicit incorporation of zooplankton for food web assessments. PNNL proposes conducting this work through the following tasks.

Project Components – Key Objectives

***Task 1*: Project Management, Meetings, and Development of a QAPP**

PNNL will manage all tasks and deliverables and monitor the progress via task list consisting of task name, status (ie., %complete), budget expended, duration, start and finish end dates etc. PNNL will provide a progress report with each monthly invoice, report accomplishments covered by that invoice and percent complete for each task. PNNL will include the updated detailed task list with each invoice. PNNL will also attend weekly phone collaboration meetings with USEPA to discuss project progress and analysis of data and results.

A Quality Assurance Project Plan (QAPP) with detailed scope of work to be accomplished under each task will be developed in collaboration with USEPA. PNNL has assumed that a QAPP document consistent with the National Estuary Program guidelines will be required. QAPP materials will identify the data sources to be evaluated and variables and locations of interest for reporting. QAPP will include a breakdown of activities under each task and schedule of activities to be completed with a description of milestones and deliverables. PNNL expects that the QAPP will include information on data availability and model application and performance targets. These will be developed using input from end user scientific communities which in this case will include representatives from Washington State Department of Fish and Wildlife (WDFW), Washington State Department of Natural Resources (WDNR), NOAA, and others. PNNL will host a project

[5] USEPA. February, 2016. E-mail communication(s) between Dino Marshalonis and Ben Cope of USEPA and Tarang Khangaonkar of PNNL

kick off meeting to facilitate the participation of local collaborators and the development of the QAPP document.

<u>Task 2:</u> Incorporation of TSS, Turbidity, and Light Availability in SSM

During periods of high flow, rivers generate turbidity plumes that affect light availability in the nearshore environment. There is much spatial variability in eelgrass density and phytoplankton blooms in Puget Sound, abundant in certain regions and sparse in other parts. There is a hypothesis that this spatial variability could be related to nearshore turbidity and availability of light. As part of this task, we plan to ensure spatial variability in light availability is correctly simulated through simulation of TSS and turbidity. The USGS rating curves will be used to estimate TSS loading for major rivers entering the Salish Sea. Specifically, in addition to preparing TSS loading information, the following model improvement activities will be conducted.

- Modification of FVCOM-ICM to include TSS and Turbidity
    - Development will first be conducted on a simplified channel geometry
    - The code will then be tested on Salish Sea scale with SSM
- SSM calibration to observed turbidity monitoring data
- SSM validation against available photosythetically available radiation (PAR) data

PNNL will conduct this work using TSS, turbidity and PAR monitoring data sets identified and acquired during the development of QAPP in collaboration with WDNR, Ecology, and other collaborators.

<u>Task 3:</u> Addition and Testing of Eelgrass Module to SSM

Benthic aquatic primary producers such as eelgrass, benthic diatoms, and seaweeds are critical to nearshore ecosystems and food webs in Salish Sea. The objective of this effort is to ensure that benthic primary production, on scales relevant to nearshore shellfish, and changes in benthic primary production is included in the computations of the effects of increased DIC on pH. For this study, we plan to focus on eelgrass through the incorporation of a submerged aquatic vegetation (SAV) module in SSM using an approach like the one used successfully by Cerco and Moore (2001)[6] in Chesapeake Bay. Three state variables will be used to describe the plant biomass: shoots, roots and epiphytes, where shoots are plant biomass above ground, roots are biomass below ground and epiphytes are attached biomass growth. Overall model development activities will include the following major components

- *Model development* - Modification of FVCOM-ICM to include SAV module (eelgrass). Development will be conducted on a simplified channel geometry
- *Model Application to Salish Sea* - Application to Salish Sea using available information on eelgrass density and the SSM domain

These two objectives will be accomplished through the following steps

---

[6] Cerco, C.F. & Moore, K. System-wide submerged aquatic vegetation model for Chesapeake Bay *Estuaries and Coasts* (2001) 24: 522. doi:10.2307/1353254

- *Step 1* - Review of SAV models and efforts in Chesapeake Bay, as well as data collected in Puget Sound from WDNR and PNNL/MSL lab experiments.
- *Step 2* - Implementation of SAV model using a single water column setup (box model) for initial testing of growth/mortality within a specified nutrient/light environment
- *Step 3* - Testing of steady state and time series solutions for the box model of SAV root, stem, and leaf biomass, based on laboratory experimental or literature data
- *Step 4* - Coupling of SAV model with nutrient cycling, and sediment diagenesis, including light attenuation effect due to self-shading
- *Step 5* - Conducting setup and testing FVCOM-ICM SAV model in simple channel case
- *Step 6* - Conducting setup and testing of FVCOM-ICM SAV model in for the Salish Sea

The planned implementation will be a simplified model that carries out time dependent changes of eel grass biomass (leaf, stem, root) and nutrient fluxes associated with eel grass. Multiple species can be modeled independently but this effort will focus on one dominant representative species of eel grass in Puget Sound. This effort will not include model capability development to address area expansion/shrinkage of eel grass meadow or interaction of multiple eel grass species. Similarly, eel grass impact on hydrodynamics is beyond the scope of this first effort.

Note: Primary productivity data on the major benthic primary producers gathered from a variety of sites in Puget Sound is available for model setup from WDNR (http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/puget-sound-eelgrass-monitoring-data-viewer.) Use of this data and other available sources will be discussed in QAPP. However, it is noted that multi-year calibration to available eelgrass data is beyond this scope of this phase of model development work.

***Task 4:* Addition of Zooplankton Kinetics to SSM**

Zooplankton kinetics in the FVCOM-ICM model of Salish Sea will be based on Cerco and Noel (2004) implementation of CE-QUAL-ICM for Chesapeake Bay. Two classes of zooplankton are available: micro-zooplankton and macro-zooplankton. Zooplanktons interact with algae, bacteria, particulate organic matter, dissolved organic matter (DOM), and fish. In the existing SSM, zooplankton effect on phytopkankton was incorporated through the specification of predation rate. Zooplankton were not simulated explicitly. The present work will activate zooplankton module and mainly focus on zooplankton growth by grazing algae and mortality pathways to particulate organic matter and dissolved organic matter. Predation of micro-zooplankton by macro-zooplankton is used to reflect their direct interactions. The model is carbon based and basal metabolism is regulated by temperature. Mortality due to low dissolved oxygen is also included in the model. We propose to activate and test the zooplankton model for variability of its effect on algae, carbon cycling and dissolved oxygen.

The zooplankton model development and implementation will be conducted in following steps.

- *Step 1* - Review prior zooplankton model development efforts in CE-QUAL-ICM model and its application to Chesapeake Bay
- *Step 2* - Implementation of zooplankton module in FVCOM-ICM code
- *Step 3* - Testing of zooplankton, algae, and nutrient interaction/cycling in a simplified idealized channel setting
- *Step 4* - Processing and preparation of available zooplankton data from Puget Sound area for model calibration
- *Step 5* - Setup and testing of FVCOM-ICM zooplankton model for Salish Sea

We expect that model setup for the Salish Sea domain will be accomplished using zooplankton data collected through the Puget Sound wide monitoring program implemented by University of Washington, Ecology, King County and partners since 2014 as part of the Salish Sea Marine survival project by Long Live the Kings (http://marinesurvivalproject.com/research_activity/list/zooplankton-establishing-puget-sound-wide-zooplankton-sampling-program/). These data will be identified and described during the QAPP preparation task.

Task 5: **Re-calibration of SSM Biogeochemistry with Zooplankton and Eel grass**

In this important final step, we will eliminate the hard-wired dependence of algae growth and die-off cycles on temperature alone that are presently specified in SSM. Temperature preference for growth will continue to be a part of the kinetics. However fixed algal predation rate will be replaced with one dependent on zooplankton biomass. This will allow correct coupling and interaction between the two species of algae, their growth and consumption by two zooplankton species and nutrient balance. In the model calibration, we will also have sediment diagenesis and carbonate chemistry active resulting in a complete nutrient, phytoplankton, zooplankton, and detritus or particulate organic matter (NPZD) calibration for the Salish Sea. For eel grass, a set of calibration sites will be selected based on availability of data and studied with respect to simulation of eel grass biomass distribution. The eel grass component will be represented by SAV model parameters and proper initialization will be needed as eel grass may take up to 10-15 years to reach the state of full development.

The SSM solutions will now include all water quality variables including DO, pH, phytoplankton, and zooplankton concentrations that may be fed directly into the Altlantis Model (ecosystem food web) of Salish Sea being developed by NOAA Fisheries Science Center. The eel grass results will include areas of eel grass coverage, and representative leaf, stem and root biomass concentrations (gC/m^2/bottom area). The nutrient cycling and competition for food between phytoplankton and eel grass will be included explicit through direct coupling in this version of SSM.

Note – In this first effort, our objective will be to get the Salish Sea domain-wide biogeochemical model up and running with full coupling between nutrients, zooplankton, detritus, and submerged aquatic vegetation using a target year for model development and calibration. Multiyear application and testing is beyond the scope of this phase of model development work.

***Task 6:* SSM Plume Mixing and Transport Model**

(This task is independent of the TSS/Turbidity, SAV, and Zooplankton additions to SSM discussed in prior tasks)

There is a growing interest in utilizing SSM solutions to examine the exposure of shellfish and other sensitive sites to toxics and organic particles discharged from wastewater and stormwater outfalls. Effects of discharges from shipping traffic is another issue of interest. Although SSM operates on an unstructured grid, its refinement for addressing each outfall at the resolution of outfall pipe is not practicable. Instead, a tool designed to simulate effluent dilution and mixing from outfalls dynamically coupled to SSM is needed. [Note: - This is different from CORMIX and UM models that provide steady state solutions for nearfield Mixing Zone analyses using fixe ambient conditions].

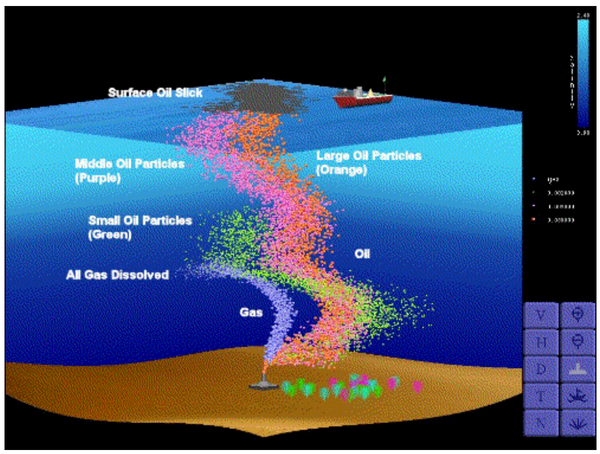

Figure 1 Example of simulation and visualization of an effluent Plume. [*Source*: Dr. Poojita Yapa of Clackson University - Comprehensive Deepwater Oil and Gas Blowout Model CDOG Model]

Tools of this nature that utilize particle tracking as a preferred method of visualizing plumes have been used extensively in the oil spill trajectory modeling. Their use and adaption for fate and transport of pollutants from outfalls is relatively new and is proposed here.

In this task PNNL proposes development of a plume transport modeling and visualization tool to conduct exposure assessment using SSM. This tool will operate within the Salish Sea domain boundaries constrained by the SSM bathymetry. The plume transport tool will use hourly (or 15-min) interval solutions consisting of water surface elevation, currents, and salinity and temperature profiles. The plume model will incorporate jet/plume hydrodynamics and thermodynamics and simulate effluent plume dilution and far-field transport. The SSM-Plume model will be calibrated against established EPA Plume models such as CORMIX or UM before application to the Salish Sea domain. The product of this effort will be the ability to conduct fate and transport analysis and visualization of discharges from arbitrary locations within Salish Sea to examine their impacts on the surrounding environment.

In collaboration with Clarkson University and Dr. Poojita Yapa, this work will be conducted at PNNL with assistance from a doctoral student of Dr. Yapa who will visit PNNL as a doctoral student intern during the summer of 2017 and likely continue the work as a Post Doc in FY18.

***Task 7:* Draft and Final Report**

PNNL will prepare a draft report describing the FVCOM-ICM Salish Sea modeling system and the refinements and improvements accomplished. The report will provide details on model development include calibration and verification runs focusing on zooplankton and eelgrass as these are new models for the Salish Sea region. Effect of zooplankton on phytoplankton kinetics and impact of eelgrass on nutrients, DO and pH will be discussed. PNNL will share the draft with USEPA for peer review and comment. After receiving comments PNNL will incorporate the comments and submit the final report as the deliverable for this IGA.

Schedule:
Start Date: 10/5/2017 End Date: 9/30/2019

Project Timeline:

	FY Year	2018				2019			
Tasks	**Quarter**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1.0 Preparation of QAPP									
2.0 Incorporation of TSS, Turbidity, and Light									
3.0 Addition of Eelgrass Module to SSM									
4.0 Addition of Zooplankton Kinetics to SSM									
5.0 Re-calibration of SSM with the Improvements									
6.0 Plume Mixing and Transport Model									
7.0 Report / Publication(s)									

Anticipated Outputs and Outcomes:

The primary outputs of the proposed tasks will be SSM improvement, application, testing, and the development of post processing procedures along with associated deliverables consisting of a combination of reports and power point presentations. This includes a QAPP document (Task 1) and a working and calibrated version of SSM with improvement described in the tasks above. Specifically, the improved SSM will include the new capability of predicting turbidity and light availability (Task 2). SSM will also have submerged aquatic vegetation / eel grass which will participate in the biogeochemical balance calculations for the Salish Sea (Task 3) and with explicit simulation of zooplankton kinetics (Task 4). The improved model will be calibrated to data from Year 2014/2015 period (Task 5). A new tool will be developed to compute dynamic effluent plume transport using SSM solutions (Task 6). The results of this effort will be summarized in a study report (Task 7)

Statement of Shared Interest:

PNNL is a U.S. Department of Energy (DOE) – National Laboratory based in Richland, WA. It is the only DOE laboratory with a Coastal Sciences Division and a Marine Sciences Laboratory, located in Sequim, WA. As a DOE laboratory, PNNL has significant scientific manpower and computational capabilities available to share with collaborating government agencies. PNNL has made a conscious decision to support and participate in the Puget Sound Restoration efforts through the development of the *Salish Sea Model* for use by agencies responsible for management of water quality and the ecosystems in Puget Sound and the greater Salish Sea. Scientists from PNNL are making PNNL Institutional Computing power and associated complex ocean modeling tools accessible to the community through inter-governmental collaborative agreements. USEPA's National Estuary Program has been the primary sponsor of the Puget Sound Restoration efforts since 2009. USEPA and the partnering agencies recognize the importance of a predictive tool such as the SSM to guide regional strategies and specific actions needed for the recovery. The SSM is already being used by USEPA and Ecology for the analysis of circulation, water quality, and ecosystem response for nutrient pollution management, sea level rise, climate change, and ocean acidification. USEPA is exploring opportunities to partner with other states / regional entities to develop site specific models based on SSM.

Environmental Significance:

Despite best intentions, efforts to restore nearshore habitats and ecosystems can result in poor outcomes if water circulation and biogeochemical processes are not properly addressed. Land use constraints can lead to selection of suboptimal restoration alternatives that may result in undesirable consequences, such as flooding, deterioration of water quality, and erosion, that require immediate remedies and costly repairs. Quantitative models designed for application to the nearshore environment can minimize uncertainty about restoration goals, such as recovery of tidal exchange, supply of sediment and nutrients, and establishment of fish migration pathways. As the leading comprehensive predictive model of Salish Sea, SSM is expected to become a strategic water pollution control and water quality management and planning tool for use by regulatory agencies for the present and future conditions given, climate change, sea level rise, and population growth considerations.

PNNL and EPA Contribution:

PNNL will conduct all tasks under the guidance and oversight from USEPA in collaboration with state agency partners such as WDNR and Ecology. All work will be conducted on PNNL's Institutional Computing (PIC) located in Richland.

Project Deliverables:

Task 1: Project Management, Meetings, and Development of a QAPP
PNNL will prepare monthly progress reports, participate in monthly progress meetings, and develop presentation materials as needed. A major deliverable in this task will be preparation of a QAPP document with details on data availability and model application and performance targets.

Task 2: Incorporation of TSS, Turbidity, and Light Availability in SSM
A PowerPoint progress presentation detailing the model improvement steps incorporating TSS, Turbidity, and Light availability in SSM. Model calibration will be against measured turbidity and PAR data

Task 3: Addition and Testing of of Eelgrass Module to SSM
A PowerPoint progress presentation detailing the model improvement steps incorporating eelgrass module in SSM. Model calibration will be against measured eel grass biomass data and other data available from WDNR.

Task 4: Addition of Zooplankton Kinetics to SSM
A PowerPoint progress presentation detailing the model improvement steps incorporating zooplankton module in SSM. Model calibration will be against measured zooplankton data from recently completed plankton studies by NOAA and organizations such as Long Live the Kings.

Task 5: Re-calibration of SSM with Zooplankton and Eel grass
A PowerPoint progress presentation demonstrating model skill against monthly monitoring data collected by Ecology at 26 stations around Puget Sound. This deliverable will serve as a skill assessment test and demonstrate that the upgraded SSM performs well with a focus on parameters such as DO, pH, and algal biomass.

Task 6: SSM Plume Mixing and Transport Model
A PowerPoint progress presentation demonstrating the status of plume model development with application to simplified channel and comparisons to EPA plume models such as Visual Plume or CORMIX

Task 7: Report / Publication(s)
Draft and final study reports for review and comments by USEPA prior to finalization and publication